2.0 BASIC CONCEPTS OF OPEN CHANNEL FLOW MEASUREMENT

Open channel flow is defined as flow in any channel where the liquid flows with a free surface. Open channel flow is not under pressure; gravity is the only force that can cause flow in open channels and a progressive decline in water surface elevation always occurs as the flow moves downstream (BOR, 1997). Examples of open channel flow at mine sites include: rivers, streams, creeks, discharges from tailings ponds, and other uncovered conduits. Closed channels, such as adits, tunnels, and ventilation shafts, can be treated as open channels when flowing partially full and not under pressure.

The purpose of Section 2.0 is to briefly introduce the reader to basic terminology and concepts related to open channel flow to allow for a simpler and more accurate presentation of the flow measurement techniques and methods in Section 3.0. A working knowledge of these concepts and relationships is extremely important in selecting the appropriate measurement tool as well as siting, calibrating, and collecting data from the chosen measurement device. This section is included as a supplement to this document and offers background information that some readers may already understand. It is not meant as a complete discussion of each concept but more as a summary discussion. Cited references offer more in depth explanations if desired.

2.1 BASIC WATER MEASUREMENT CONCEPTS

Most open channel water measuring devices or methods calculate stream discharge from a combination of head, stage, and velocity measurements with respect to a common reference point. These terms are described below:

2.1.1 Gage Datum

Gage datum is a common elevation selected as a reference point for subsequent measurements and calculations pertaining to gage installation, calibration, and operation. The datum may be a recognized datum (e.g., mean sea level) or an arbitrary datum chosen for the convenience of measuring gage heights in relatively low numbers. When using an arbitrary datum, the datum selected for gage operations should be below the zero flow, or no flow elevation to eliminate the possibility of negative gage heights (Buchanan and Somers, 1982).

A permanent datum should be maintained to ensure that the gage-height record uses the same datum for the life of a gage. The permanent datum can be maintained by establishing two or three reference marks that are independent of the gage. The reference marks are periodically checked to make sure the datum is fixed in the same location. Establishing reference marks independent of the gage allows the datum to be reestablished if the gage is damaged or destroyed (Buchanan and Somers, 1982).

2.1.2 HEAD

Head is an engineering term frequently used in water measurement equations and practice. Under open channel flow conditions, head is the difference in elevation, relative to a specific datum, between the water surface elevation at locations upstream and downstream of the water measurement location. The resulting pressure on the fluid at the downstream point is expressible as the elevational difference, or head. Head can also be expressed in terms of differences in pressure.

2.1.3 STAGE

Stage is the height of the water surface above an established datum plane. Stage measurements are often used or incorporated into calculations to determine stream discharge within a particular channel reach. Stage is typically measured with a staff gage, a fixed scale measuring device installed in a primary measuring device (Section 3.0) or in an open channel reach where the channel configuration and channel geometry is well-defined. Staff gages are often mounted vertically; however, greater accuracy can be obtained by inclining the staff so that the graduations are larger for a given change in water surface elevation (Grant and Dawson, 1997). The water surface elevation (i.e., stage) read from the staff gage is commonly called the gage-height.

2.1.4 VELOCITY

The Manning equation relates velocity to total bed resistance or friction to calculate flow velocity (*V*). The equation balances the gravitational acceleration of water in an inclined, open channel against surface area and bed roughness. The Manning equation is intuitively appealing because of its simple form:

$$V = \frac{1.49}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

where:

V = flow velocity, feet per second
n = Manning roughness coefficient
R = hydraulic radius, feet
S = longitudinal slope, feet per foot

Manning's n is a dimensionless number that defines the flow resistance of a unit of bed surface. Resistance is a function of particle size, bed shape, and constructional bed forms (e.g., ripples).

Manning's n incorporates many physical factors including the channel roughness, irregularity of the channel cross section, channel alignment and bends, vegetation, sedimentation, scouring, and channel obstructions (Barfield et al., 1981). Table 2-1 presents a list of commonly used values for Manning's n.

Table 2-1. Typical Values for Manning's n

Type and Description of Conduits	**Min.**	**Design**	
Earth bottom, rubble sides	0.028	0.032	0.035
Drainage ditches, large, no vegetation			
<2.5 hydraulic radius	0.040		0.045
2.5 - 4.0 hydraulic radius	0.035		0.040
4.0 - 5.0 hydraulic radius	0.030		0.035
>5.0 hydraulic radius	0.025		0.030
Small drainage ditches	0.035	0.040	0.040
Stony bed, weeds on bank	0.025	0.035	0.040
Straight and uniform	0.017	0.0225	0.025
Winding, sluggish	0.0225	0.025	0.030
(A) Clean, straight bank, full stage, no rifts or deep pools	0.025		0.033
(B) Same as (A) but some weeds and stones	0.030		0.040
(C) Winding, some pools and shoals, clean	0.035		0.050
(D) Same as (C), lower stages, more ineffective slopes and sections	0.040		0.055
(E) Same as (C), some weeds and stones	0.033		0.045
(F) Same as (D), stony sections	0.045		0.060
(G) Sluggish river reaches, rather weedy or with very deep pools	0.050		0.080
(H) Very weedy reaches	0.075		0.150

SOURCE: Barfield et al. (1981)

Hydraulic radius (R) can be approximated for parabolic channels where the water surface width is >> than the depth of the water as:

$$R = \frac{2}{3} d$$

where d is the average depth. For channel geometries that approximate trapezoidal or rectangular cross sections and where the bottom width is >> than the average depth, R is approximately equal to average depth (d). The hydraulic radius of a stream with a triangular cross section can be approximated as $0.5d$ (Barfield et al, 1981). Uncertainties associated with the Manning equation can be minimized by basing the variables on accurately measured data. Specifically, the channel cross section should be surveyed to obtain accurate measurements of width, depth, and hydraulic radius.

The actual distribution of flow velocity is generally quite complex. Open channel flow is often laminar or near-laminar, with the different layers moving at different velocities. Flow velocity at the contact point with the channel boundary is low (Barfield et al., 1981). Typically, the highest velocity flow is located in the center of the flow channel and slightly below the water surface. Figures 2-1 and 2-2 present typical velocity profile and a typical vertical velocity distributions under open channel flow conditions. A general knowledge of velocity distributions is extremely important in evaluating and selecting a method of flow measurement. Sites with irregular or complicated channel geometries, such as meanders or riffle areas, can cause a decrease in measurement accuracy when using methods that rely on velocity measurements to calculate discharge. These methods and factors associated with the proper siting for measurements are described in Section 3.0.

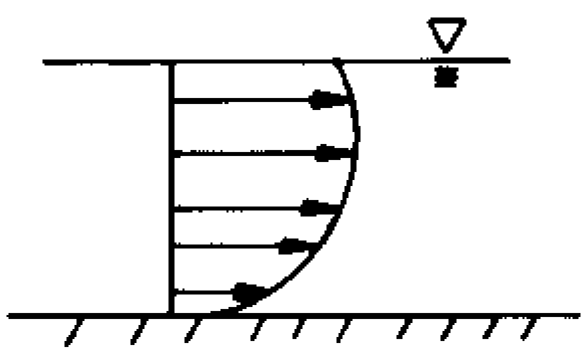

Figure 2-1. Typical Open Channel Velocity Profile (Barfield et al., 1981)

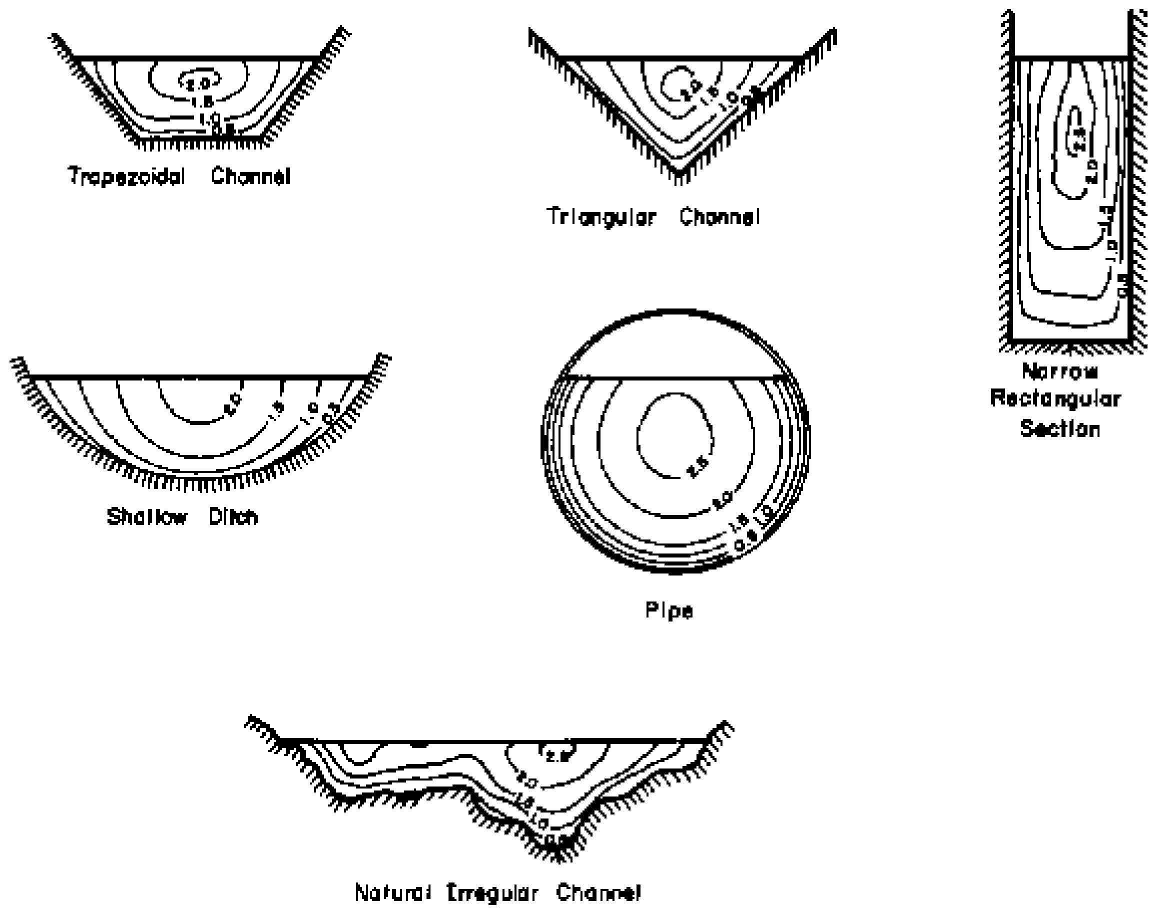

Figure 2-2. Typical Velocity Distributions for Several Channel Profiles (Barfield et al., 1981)

2.1.5 Discharge

Discharge is the volume of water per unit time flowing past a set point or station. Open channel discharge is commonly reported in cubic feet per second (cfs) or cubic meters per second (cms). Gallons per minute (gpm) is the common unit of measure used in studies to evaluate and predict mine site water balances. Gpm is also the common measurement unit for reporting industrial and wastewater treatment plant discharges. Many discharge measurements made at mine sites and from mine facilities, therefore, are converted to gpm in order to evaluate their association with the water balance for the mine.

A series of discharge measurements made at a gaging station is often used to define a discharge rating curve for a site. A discharge rating curve may be a simple relationship between stage and discharge, or a more complicated relationship that includes stage, slope, rate of stage change, and other factors (Carter and Davidian, 1968). Most methods and devices for measuring flow are designed to calculate stream discharge.

Discharge (Q) is generally expressed in cfs and is calculated from:

$$Q = VA$$

where V is the average flow velocity at a cross section, in feet per second (ft/s), and A is the area of that cross section, in square feet (ft^2) (Barfield et al., 1981). The Manning equation (Section 2.1.4) can be used to estimate average flow velocity (*V*). To obtain discharge (*Q*) in units besides cfs, the constant of 1.49 in the Manning equation can be changed to 669 if discharge (*Q*) will be reported in gpm, or 1.00 for liters per second (l/s) (Grant and Dawson, 1997). The primary measuring devices presented in Section 3.0, however, provide more accurate estimates of discharge than can be obtained using the above equation combined with estimates of average velocity obtained by the Manning equation.

2.2 OPEN CHANNEL FLOW RELATIONSHIPS

Open channel flow occurs under one of three possible flow conditions: sub-critical; critical; or super-critical. Three basic relationships govern open channel flow: the continuity equation, the momentum equation, and the energy equation. Each of the relationships is briefly described in the following sub-sections. The reader is encouraged to consult some of the hydrology and hydraulic engineering texts listed in the reference section for more information.

2.2.1 Continuity Equation

The continuity equation is a simple mass balance and can be written as:

$$Inflow - Outflow = \Delta Storage$$

where inflow represents the volume or rate of flow across an upstream cross-section during time t and outflow is the volume or rate of flow across a downstream cross section during time t. The change in storage (Δstorage) is the rate or volume at which water is accumulating or diminishing within the section.

2.2.2 Energy Equation

The energy equation, also known as Bernoulli's theorem or equation, is given by:

$$\frac{V_1^2}{2g} + y_1 + z_1 + \frac{p_1}{\gamma} = \frac{V_2^2}{2g} + y_2 + z_2 + \frac{p_2}{\gamma} + h_{L,1-2}$$

where:

V	=	average flow velocity, feet per second
g	=	gravitational constant, 32.2 feet per second squared
y	=	depth of flow, feet
z	=	elevation of the channel bottom above some datum point, feet
p	=	pressure, pounds per square foot
γ	=	unit weight of water, 62.4 pounds per cubic foot
$h_{L,1-2}$	=	represents the energy loss between section 1 and 2, feet

Bernoulli's equation, which represents an energy balance between two points along a channel, is graphically depicted in Figure 2-3.

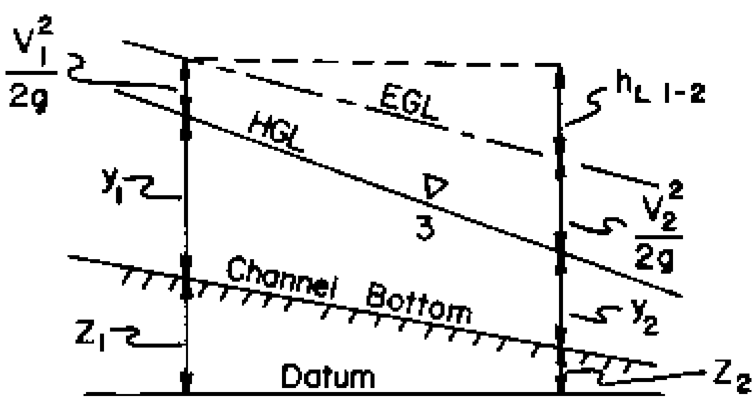

Figure 2-3. Graphical Representation of the Terms in Bernoulli's Equation for an Open Channel (Barfield et al., 1981)

Each complete term in the equation has the units of length and each term is associated with a "head." The term $V^2/2g$ is the velocity head, $y + z$ is the elevation head, and p/γ is the pressure head (Barfield et al., 1981). Total energy is the sum of the velocity head, pressure head, and elevation head and is represented by the energy grade line (EGL) in Figure 2-3. The hydraulic grade line (HGL) is the sum of the elevation head and the pressure head. In open channel flow, the free water surface is exposed to the atmosphere so the pressure head is equal to zero. The water surface is represented by the HGL under open channel flow conditions.

Bernoulli's equation can be used to derive the Froude number (Fr) for a given stream reach. The Froude number is a dimensionless number defining the type or degree of water turbulence in a reach. The Froude number, the ratio of the inertia force to the force of gravity, can be used to distinguish between sub-critical, critical and super-critical flows. Critical flow occurs when the Froude number is unity (i.e., 1), inertial forces are equal to gravitational forces. Critical flow is unstable, tending towards one of the other two conditions. A Froude number less than unity (i.e., inertial forces are less than gravitational forces) indicates sub-critical flow. Sub-critical flow is laminar with each element of fluid moving in approximate parallel paths with uniform velocity. A Froude number greater than unity (i.e., inertial forces are greater than gravitational forces) indicates super-critical flow. Super-critical flow is turbulent, characterized by breaking surface waves and increased resistance to flow. The Froude number associated with a given reach has important implications for flow measurement, and sediment loading, transport, and erosion. Flow measurements are typically taken in reaches with sub-critical or critical flow. Very few methods can accurately measure stream discharge in stream reaches with super-critical flow. The Froude number (Fr) can be calculated from:

$$Fr = \frac{V}{\sqrt{g h_m}}$$

where V is velocity (fps), g is the gravitational constant, and h_m is hydraulic mean depth (ft). Open channel flow measurement generally requires Fr of the approach flow to be less than 0.5. Sub-critical approach flows avoid wave action that could hinder or prevent accurate flow readings (BOR, 1997).

Experience and knowledge regarding sub-critical, critical, and super-critical flow are extremely important in determining a method for measuring discharge and in siting a location for measurement. For example, water measurement flumes function best when flow is forced through the flume at a depth where flow is critical. At critical depth, discharge can be measured using one upstream head measurement station. Moreover, calibration of weirs and flumes is simplified because these measurement devices have one unique head value for each discharge (BOR, 1997).

2.2.3 Momentum Equation

The momentum principle states that the sum of forces in a given direction is equal to the change in momentum in that direction. M is a constant that represents the specific force plus momentum. In a short reach where frictional resistance is insignificant and the channel slope is small (i.e., the sine of the channel slope approaches zero), M can be derived from (Barfield et al., 1981):

$$\frac{y_1^2}{2} + \frac{qV_1}{g} = \frac{y_2^2}{2} + \frac{qV_2}{g} = M$$

where:

M = specific force plus momentum constant
y = depth of flow, feet
V = average flow velocity, feet per second
g = gravitational constant, 32.2 feet per second squared
q = flow rate per unit of width, ft^2/sec or cfs/ft

Figure 2-4 is a graphical representation of a plot of depth (*y*) versus *M* for a constant *q*. Every *M* has two possible depths and a definite minimum. At the minimum *M* (y_c on Figure 2-4), specific energy is minimum and only a single flow depth occurs. This condition is referred to as critical flow ($_{y.}$).

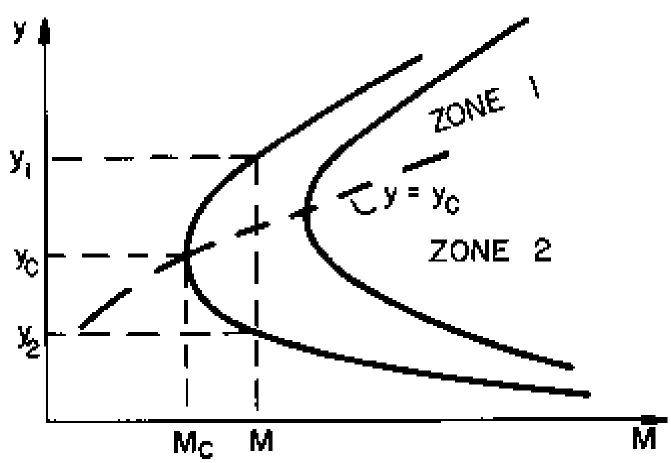

Figure 2-4. Typical Specific Force plus Momentum Curve (Barfield et al. , 1981)

Super-critical flow (y_2) occurs when depth is less than critical and velocity is greater than the critical condition. When depth is greater than critical and velocity is less than critical the flow is termed sub-critical (y_1) (Roberson et al., 1988). As previously noted, experience and knowledge regarding sub-critical, critical, and super-critical flow are extremely important in determining a method for measuring stream discharge.